

GROUND SYSTEM DEVELOPMENT AT THE MOREHEAD STATE UNIVERSITY FOR INTERPLANETARY SMALLSAT MISSIONS

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ABSTRACT

As more small satellites are used for interplanetary research and exploration, more ground antennas with sufficiently large aperture are needed to support the increased demand in deep space communication. The 21-m ground antenna at the Morehead State University in Kentucky, United States is under development to upgrade its telemetry, tracking and command capability at X-band. The system architecture is based on a hybrid design that combines commercially available products with specialized equipment developed for the National Aeronautic and Aerospace Administration's Deep Space Network. This architecture produces a low-cost and geographically diverse system, connecting elements at the Morehead State University and those of the DSN at the Jet Propulsion Laboratory in Pasadena, California. The architecture makes Morehead antenna appears as one of the DSN nodes, albeit with a different performance metrics due to difference in aperture size. Its operation is geared for automation, with automated data retrieval of information needed for configuring the ground station for spacecraft tracking. An incremental testing approach is used to verify system capabilities as various components are deployed into the system.

1 INTRODUCTION

CubeSats and other small satellites are increasingly used for Earth remote sensing, for science research, and for unique communications activities, all of which have increasing data throughput requirements. In addition, CubeSats are being planned for interplanetary research, with 13 CubeSats slated to fly on the NASA's Exploration Mission-1 (EM-1) in 2019, opening the door for CubeSat and smallsat exploration of the solar system. As these Cubesat missions venture to the distance of the moon and beyond to other bodies within the Solar System, they require a ground tracking system with greater capabilities than previously required for low Earth orbiters. Performance attributes in the ground system such as large antenna, high gain efficiency, operation at higher performing X-band frequency, low noise and low-loss equipment, most efficient forward error correction coding, high transmitting power, etc. become critical to the communications with deep space spacecraft.

Given the expected significant increase in Cubesat missions, beyond what is currently supported by the NASA Deep Space Network (DSN), the NASA Advanced Exploration Systems (AES) program has been funding an implementation at the Morehead State University to enable its 21-m antenna to

support the Lunar IceCube mission and other EM-1 Cubesats. Leveraging on the expertise in deep space communications of the Deep Space Network, a partnership between the Jet Propulsion Laboratory (JPL) in California, United States and the Morehead State University (MSU) in Kentucky, U.S., was established to help with the development of ground station at Morehead, and to develop a strategy that would enhance DSN capabilities by utilizing existing non-NASA assets (i.e. university and non-profit radio astronomy observatories). Our goal is to build a ground station that is capable of deep space communications and tracking, with maximum compatibility with the DSN, and within limited budget. The approach we took is to optimally combine the specialized DSN equipment with commercially available components. This hybrid system minimizes development cost from not having to spend money on the non-recurring engineering for special deep space signal processing capabilities that already exist in the DSN. It also allows the Morehead technical staff and students the opportunities to design and develop their own system, using commercially available products; thus, offers a learning opportunity to the students and, at the same time, meeting the low-cost objective.

In Section 2 of this paper, we describe the Morehead ground system architecture that strives for maximum capability with minimal cost, using a hybrid approach mentioned above. Such an architecture allows the MSU ground system to serve as a node on the Deep Space Network, to help offsetting the DSN loading for certain class of missions such as Cubesats. In Section 3, we present a nominal operational concept on how the system is expected to operate. Telemetry, tracking and command data flows will be described, along with service management aspects such as the antenna scheduling and generation of predicted Doppler frequencies, antenna pointing, and signal conditions. We highlight key system performance metrics in Section 4. Finally, the system validation approach that relies on both test signal source and spacecraft that are currently (or soon to be) in operation, are described in Section 5.

2 SYSTEM ARCHITECTURE

Prior to this implementation effort which started in 2016, the Morehead State University 21-m antenna has been used to support several educational research picosatellites and nanosatellites such as KySat-1, KySat-2, and the Cosmic X-band Background Nanosat series (CXBN and CXBN-2). The system was also used for short-term capability demonstrations with NASA flight mission such as the Lunar Reconnaissance Orbiter and the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) [1]. Most recently, the system served as the primary ground station for the Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) cubesat, funded by the Jet Propulsion Laboratory (JPL) in collaboration with the Massachusetts Institute of Technology (MIT). The 21-m antenna, prior to this upgrade, was equipped with a replaceable feed that can support operations at various frequencies in the Radio Frequency (RF), specifically the UHF-band (400- 470 MHz), L-band (1.4 – 1.7 GHz), S-band (2.2 – 2.5 GHz), C-band (4.8 - 5 GHz), X-band (7.0 – 7.8 GHz), and Ku-band (11.2 – 12.7 GHz). Signal reception is available at all these frequency bands and transmission is available at UHF and S-band.

For the EM-1 Cubesat missions, communications between flight and ground systems will be at X-band, to maximize the link performance. The ground system will have new equipment to transmit signal at 7.1-7.2 GHz and to receive spacecraft signal at 8.4-8.5 GHz. A new X-band antenna feed will need to be developed. On the uplink, a 2-kW transmitter will be deployed, along with the exciter electronics for generation of command and ranging signals. On the downlink, a cryogenic low noise amplifier operating at a very low noise temperature of 11 Kelvins will help to maximize the signal detection. A low-loss DSN-based receiver with its associated telemetry decoding and ranging processors that are optimized for low signal-to-noise (SNR) condition normally seen in

deep space communications will also be deployed. These enhancements, relative to capability in previous missions, extend the communications to spacecraft that travel to the Moon and beyond – a 1000 times further than the low Earth orbits.

For past mission support, the MSU ground station could transmit telecommand to spacecraft and receive telemetry data; however, there was no ranging measurement required for the navigation of these nanosatellites. For future missions like the Lunar IceCube, ranging capability is essential in navigating the spacecraft to the moon. Another new challenge is the use of highly efficient error correcting codes, such as Turbo codes, which perform very close to the Shannon limit of the information channel capacity. Unfortunately, there was difficulty in finding commercial products that could support these two functions within available budget. As a result, a hybrid architecture that merges the university-developed hardware with some DSN-developed signal processing components was selected. The university focuses on RF analog components, using commercial parts available from other projects as well as some newly procured components. The digital portion of the system that process command, telemetry and radiometric (Doppler and ranging) are replica of DSN equipment. This architecture enables the MSU ground station to act as a DSN node of operations since it has the same data interfaces to mission users as other DSN antennas. Since the DSN-provided equipment supports the data interfaces in compliance with the Consultative Committee for Space Data Systems (CCSDS) specifications, the MSU system has an inherent benefit of interoperability with other ground stations worldwide that are CCSDS compliant.

Figure 1 shows the architecture of the Morehead ground station. The Mission Operation Center (MOC) interfaces with the Morehead Station ground station via the DSN Deep Space Operation Center (DSOC). Command data could be sent from the MOC directly to the Uplink (UPL) equipment at MSU. Telemetry processing at MSU produces the received telemetry frames, which are then relayed to the Telemetry Tracking Delivery (TTD) at JPL before being delivered to the MOC. The same delivery occurs with radiometric data of Doppler and ranging measurements. The network connection between Morehead State University and the Deep Space Operation Center at JPL is via the NASA Mission Backbone Network. This network connection has high redundancy and reliability, making it best suited for mission operations. The selected bandwidth of this connection is based on considerations of expected data rate needed for mission support and the annual rental cost. The Lunar IceCube and other EM-1 Cubesats have a maximum data rate under 1 Mbps. A decision was made to set the leased bandwidth at 5 Mbps to provide some flexibility for expanded operational needs.

There is also other ancillary equipment needed for ground station testing, calibration and operation monitoring, besides those used for telecommand and telemetry. The Test Translator with a standard CCSDS transponder ratio of 880/749 is used to convert the uplink signal from a transmitted frequency of ~7.2 GHz to a received signal at ~8.4 GHz. With the Translator loopback, the ranging delay within the ground system can be precisely measured. This station delay is then removed from the ranging measurements observed during spacecraft tracking in order to properly determine the spacecraft range. The loop back capability also enables a partial verification of the uplink and downlink equipment. By configuring the uplink equipment to generate a command data stream, feeding that signal to the downlink equipment, and being able to extract telemetry data, proper operation of uplink signal generation and downlink telemetry processing can be verified.

Another component that also aids with the monitoring of system performance is the Noise Diode Assembly (NDA). This equipment injects a known noise power into the system at a periodic frequency. By looking at the difference in power levels with and without the added noise, one can determine the noise temperature of the ground system. At MSU, such calibration is expected to be undertaken at the start of the pass, rather than continually through the pass as it is done in the DSN

antennas. This is a trade-off for a simpler design in the noise calibration.

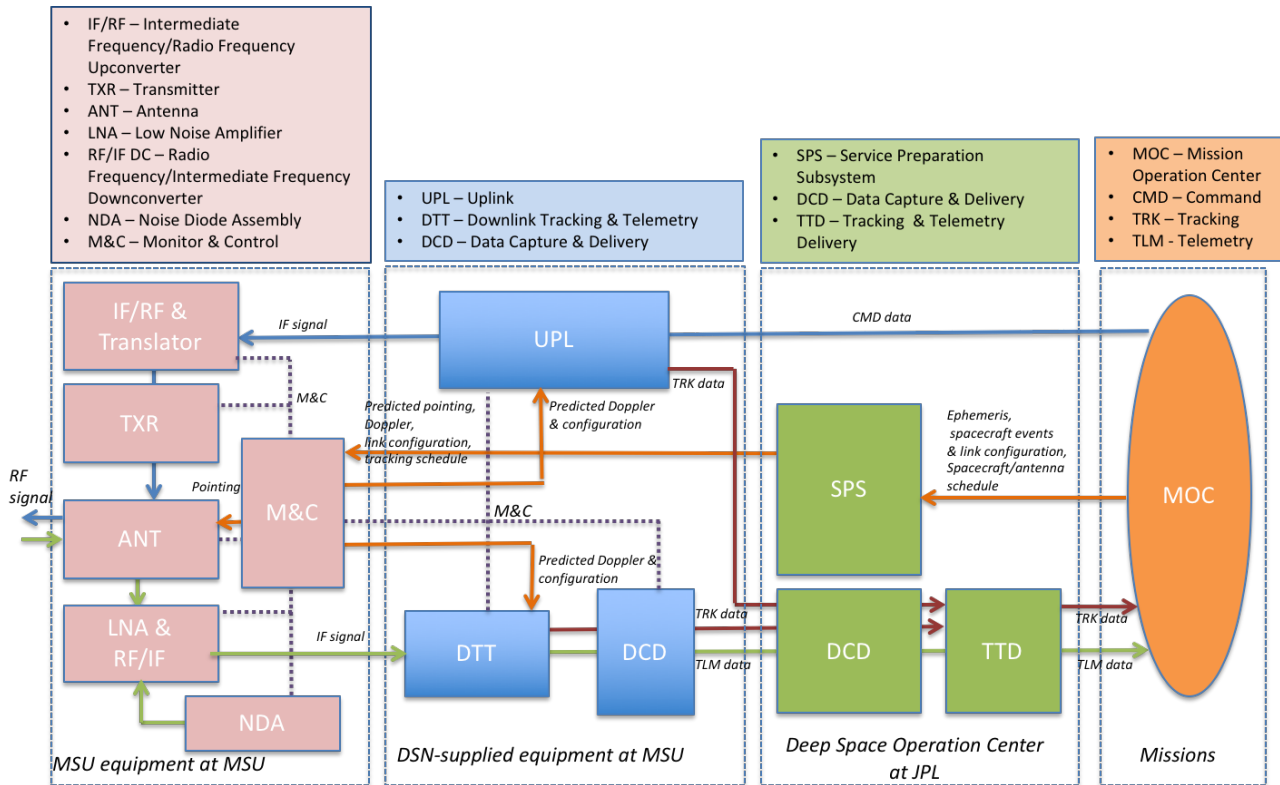


Figure 1. System Architecture

3 OPERATIONAL CONCEPT

In this section, we describe an operational concept on how the Morehead ground station operates, in conjunction with other DSN components, in support of deep space missions.

We first focus on the service management aspect of the operations. Service management refers to the antenna scheduling, generation of tracking prediction data, and equipment monitoring and configuration management.

- (1) Antenna Scheduling – The MSU antenna is schedulable by the DSN Scheduling. This allows for integrated support on missions, especially those that use both Morehead and DSN antennas. Information on any planned antenna maintenance, or science-related activities such as radio astronomy observations, will be inputted by the MSU team into the DSN schedule to indicate the time when the antenna is not available. The remaining time is open for spacecraft tracking, freely assigned by the DSN Scheduling. Through a web browser or application program interfaces, the operation team at Morehead would be aware of upcoming tracks and make necessary preparation for them.
- (2) Signal Predictions – Once a track is scheduled, predictions on the expected Doppler frequency, antenna pointing and signal conditions (e.g., data rates, signal power, coding and modulation scheme, times of signal arrival and exit) are generated by the Service Preparation Subsystem (SPS) at JPL. The required inputs for this processing are spacecraft ephemeris and expected spacecraft communications configuration (e.g., planned data rate, coding/modulation scheme, start and stop time of signal acquisition). They are submitted by

the mission operation team for their respective spacecraft. These prediction data products are automatically pulled by the Monitor/Control (M&C) processing at Morehead via a REST (Representative State Transfer) query based on the tracking schedule. The data are then distributed to appropriate equipment at Morehead - predicted pointing go to the antenna controller; expected downlink frequencies with imbedded Doppler and the expected signal conditions are given to the receiver; coding configuration is given to the decoder; uplink frequencies are given to the uplink controller, along with other configuration information necessary for command and ranging signal generation. The sequence of events for a given pass, generated by the SPS, would also indicate the start and stop time of the track, as well as any configuration changes (e.g., data rate) in mid track. Using these information, the Monitor & Control at MSU can automatically configure the equipment for the track and reconfigure the link to accommodate any subsequent changes in mid pass.

- (3) Monitor data – Monitor data from all equipment is collected by the MSU M&C and presented to the MSU operators – either an operating staff member or students. Monitor data from the DSN-provided equipment, because of the way it was built to work with the DSN monitor control infrastructure which is not deployed at Morehead due to implementation constraints, requires a special application program interface to be built to route the data to the MSU M&C. At this point, monitor data is locally stored at the MSU, rather than being routed to the DSOC and subsequently provided to MOC. In the case of anomalous event, monitor data can be extracted and delivered to the mission operation team for post-pass diagnostics.
- (4) Voice communications link – The MSU team will be able to exchange information with the DSN operations and mission operation teams via the standard DSN operational voice networks. The voice equipment supplied at MSU is the same as those used in the DSN operations center. Voice-over-internet-protocol data are flown over the same communications link that supports telemetry, command and radiometric data delivery.

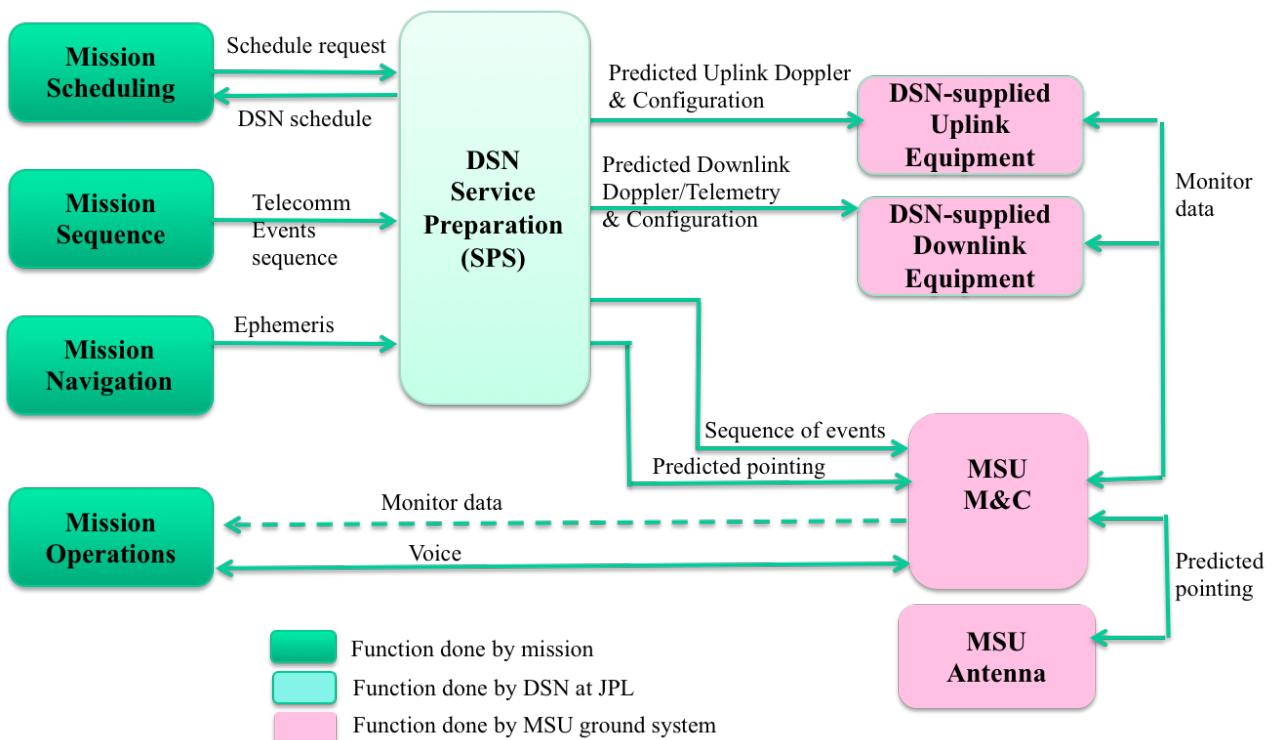


Figure 2. Service Management Data Flows

On telemetry processing, the signal received at the 21-m antenna is amplified by the cryogenic low noise amplifier and down-converted to an IF frequency around 300 MHz. The signal is then routed from the antenna to the mission control room, about 1 km away, via the fiberoptic link. The IF signal is then fed into an FPGA-based receiver that will digitize, demodulate and decode the signal. The extracted telemetry frames are sent to JPL by the Data Capture and Delivery (DCD) assembly. As the name implies, the DCD also captures and archives the data in short term, giving the option to retransmit the data should the network connection to JPL be temporarily down. At JPL, the telemetry frames are delivered to the mission operation system via an interface compliant with the CCSDS Space Link Extension (SLE) of Return All Frames or Return Channel Frames. Telemetry frames can also be further processed at JPL into packets or file products under the CCSDS File Delivery Protocol (CFDP), for missions that require this type of product to make it easier for mission operations. However, for Lunar IceCube and other EM-1 Cubesats, the mission interface is at the frame level, under the Return All Frames or Return Channel Frames service.

For radiometric data, the carrier phase and ranging phase measurements of both uplink and downlink are relayed to JPL via the DCD. The information is packed into JPL-specific data format and delivered in real time to mission operation system. The same information can also be packaged in the CCSDS Track Data Message (TDM) format, for maximum interoperability with users who use TDM format. From these data products, the mission navigation team can compute the observed Doppler and ranging, which then helps them with orbit determination for spacecraft navigation.

For command data, mission operation system will directly connect to the Uplink equipment at Morehead, using the CCSDS Space Link Extension Forward Command Link Transmission Unit (CLTU) interface specification. This SLE interface also enables user authentication and allows the mission operation team to control the radiation of commands to their spacecraft.

4 SYSTEM PERFORMANCE

Table 1 shows the improvement in the system capability at X-band, before and after this upgrade. By employing a cryogenic low noise amplifier, the system noise temperature is expected to drop by a factor of two, from 215 K to under 100K, yielding a higher signal to noise ratio and making signal detection much easier. Coupled with the use of more complex but highly efficient forward error coding such as Turbo or Low density parity check (LDPC) codes, the system can operate at a much lower signal power threshold, within 1 dB of the Shannon limit of information channel capacity.

The use of the Hydrogen MASER significantly improves the timing accuracy, by an order of magnitude compared to the previous reference to the Global Position System. This in turn improves the accuracy of radiometric data (i.e., reducing the noise in Doppler and ranging measurements), as well as telemetry data timetag.

Two significant features being added to the system with this upgrade are the ability to uplink at X-band and to conduct ranging. For ranging measurements, both DSN-specific sequential ranging [2] and pseudo-noise ranging [3] are supported. A full CCSDS-compliant pseudo-noise ranging is expected to be available in 2019.

Table 1. Pre- and Post-upgrade performance

Performance Measure	Pre-Upgrade	Post-Upgrade
X-Band Frequency Range	7.0 – 7.8 GHz	7.0 – 8.5 GHz
LNA Temperature	70 K	< 20 K
System Noise Temperature	215 K	<100 K
Antenna Gain	62 dBi (@7.7 GHz)	62.7 dBi (@8.4 GHz)
System Noise Spectral Density	-175 dBm/Hz	<-178 dBm/Hz
G/T at 5° Elevation	37.5 dB/K	40.4 dB/K
Time Standard	GPS (40 ns)	Hydrogen maser (1 ns/day)
EIRP	N/A	93.7 dBW
HPBW	0.124 deg	0.115 deg
SLE Compliance	N/A	Yes
CCSDS Compliance	N/A	Yes
Forward Error Coding	Reed Solomon/Convolutional	Reed Solomon/Convolutional, Turbo, Low Density Parity Check
Radiometric	Angle, Doppler	Angle, Doppler, Ranging

5 SYSTEM VALIDATION

The equipment delivery to the Morehead ground station is intentionally scheduled over the course of a year. We took an incremental approach to verify the system functionality and performance. As subset of equipment are delivered, local tests are done to ensure they work as expected. The scope of testing increases as more components are added to the ground system. Within each suite of tests, we focus on the functionality related to telemetry, tracking and command of the components under test.

The incremental build-up of system capability is as follows:

- (1) Installation of DSN-provided uplink, downlink, and data capture and delivery.
- (2) Connecting DSN-provided to the NASA mission backbone network for data flow to JPL.
- (3) Installation of RF equipment (feed, LNA, Downconverter) at the antenna for downlink processing.
- (4) Installation of RF equipment and Transmitter at the antenna for uplink processing.

Table 2 show the scope of testing done for each increment. At this time, we have completed increment (1) and are half-way through with increment (2). When increment (1) was completed with the delivery of DSN-provided equipment, we conducted tests by routing the uplink IF into the downlink. We were able to verify the ranging operations that involved both uplink and downlink, via the detection of good ranging correlation. Command generation by the uplink is verified via successful demodulation of the symbols (corresponding to command data) in the downlink; however, because the uplink signal is normally uncoded (since coding is normally done by the mission operations center), this loopback test was not able to verify the decoding capability of the downlink equipment. To test out the decoder operation, we relied on another external device that replayed the previously recorded signal emulating the Lunar IceCube signal that was Turbo encoded [4].

Table 2. Incremental delivery and testing

Delivery Increment	Test Focus
1. DSN-provided Uplink, Downlink and Data capture & delivery	a. Generation of command data b. Generation and correlation of ranging signal, for both sequential and pseudo-noise ranging c. Extraction of telemetry data d. Data transfer between the uplink and downlink equipment and the Data Capture & Delivery
2. Connection to NASA Mission Backbone Network	a. IP connection (after IT Security scan) b. Data delivery between the MSU DCD and JPL DCD (verifying all routing permissions in the firewall setting, both for MSU & JPL) c. Simulated data flow from DTT (at MSU) to TTD (at JPL)
3. Installation of downlink RF equipment at the antenna	a. Extraction of telemetry and delivery to JPL
4. Installation of uplink RF equipment and Transmitter at the antenna	a. Generation of command data with Transmitter in the loop, with connection from SLE user to MSU Uplink equipment b. Correlation of ranging signal, including the Transmitter and LNA components c. Radiometric (Doppler/Ranging) data delivery to JPL

After successful validation of ground equipment using the test signal, our next step is to conduct testing with the current operational spacecraft that are supported by the DSN. Because the 21-m antenna at Morehead is smaller than the 34-m (and 70-m) antennas in the DSN, and also the system noise temperature difference, there is about 10 dB difference in the received G/T. Thus, only a subset of X-band mission currently supported by the DSN, with sufficiently large margin that is above 10 dB, can be shadow tracked with the Morehead ground station, without requiring spacecraft to make any change in its telecommunications parameters. Table 3 shows a set of candidate spacecraft with sufficient margin in both command and telemetry links for Morehead ground system. There are also other spacecraft that have positive link margin on the uplink, but not on the downlink. For logistic simplicity where it is easier to test with one spacecraft that can support both uplink and downlink, only Osiris Rex and Maven, both being NASA missions, are identified in Table 3. We are exploring the option to test with these missions.

Table 3. Operational X-band missions with sufficient link margin for MSU tracking

Mission	Uplink Margin, dB	Downlink Margin, dB
Osiris Rex	20.9	5.8
Maven	17.3	5.5

Another target opportunity is the Mars Cube One (MarCO), to be launched in May-June, 2018 [5]. This mission's goal is to relay data of the Insight mission during its Entry, Descent and Landing at Mars when Insight spacecraft is not visible from Earth. This will be the first Cubesat mission that operates in deep space environment, far beyond the Earth orbit. MarCO, with its direct trajectory to Mars, will be fast moving away from Earth after launch. There is a small window of time (~ 1-2 months after launch) where the Morehead antenna can track MarCO without requiring spacecraft to lower its data rate from what is normally used with the larger DSN antennas.

In general, current operating missions are more receptive to support the testing of a new ground station if it is on a non-interference basis, i.e., not requiring spacecraft reconfiguration or affecting the data return. As such, it is easy for a new ground station to shadow-track a spacecraft and demonstrate telemetry processing. Verification of command or ranging functions require the

ground station to send a signal to spacecraft. This makes it harder to get a mission willing to support the test, due to a concern on potential impact to spacecraft operations. We hope to be able to conduct the command and ranging tests with the MarCO mission, counting on the mission's goodwill and past collaboration. In the event that the command cannot be tested with an operational spacecraft, Test 4.a. in Table 2 still gives us the confidence of command transmission, using loopback tests to validate the ground station uplink performance.

6 CONCLUSION

In summary, this paper describes a system being developed at the Morehead State University that optimally combines commercial products and specialized equipment developed for the Deep Space Network. The hybrid architecture will result in a low-cost implementation, with maximum interoperability with DSN antennas and compliance with the CCSDS specifications. Upon completion of the upgrade, the Morehead 21-m antenna system will have full operational telemetry, tracking and command capability at X-band. The system can help to offset some of DSN tracking load in time of heavy demand and is particularly applicable to future Cubesat missions due to the university's strong involvement with Cubesat communities. The system is currently undergoing testing as various components are deployed. The system has gone through partial verification using test equipment. When the system is fully deployed, testing is planned with spacecraft that are currently in operation such as Osiris Rex, Maven, as well as the upcoming MarCO Cubesat.

7 REFERENCES

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